

PEAK IMPLOSION POWER AS A PREDICTOR OF PLASMA RADIATION SOURCE K-SHELL PERFORMANCE*

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Abstract

Hawk is a current-stiff z-pinch driver that uses a plasma opening switch to transfer inductively-stored current into the load, and employs a vacuum voltmeter to directly measure the voltage drop across the neon gas-puff z-pinch. The load-voltage measurements permit calculation of the time-dependent load inductance, as well as the associated power P_{imp} and energy E_{imp} in the pinch during the implosion and stagnation phases. For experiments that determine the dependence of neon K-shell yield on the gas-puff density profile at constant load mass, P_{imp} is found to be a better measure of pinch quality and yield than peak current or implosion energy. For these data, and other data for which the load mass was varied with constant profile shape, P_{imp} and E_{imp} are combined with K-shell radiation measurements to provide insights into the physics of the pinch stagnation phase.

I. INTRODUCTION

Hawk neon gas-puff experiments to determine the dependence of K-shell yield on the plasma-radiation-source (PRS) density profile have been reported. [1] In those experiments (with 0.6-MA pinch current I and 100- to 400-ns implosion times t_{imp}), the profile was varied with nearly-constant load mass m by changing the ratio of inner to outer plenum pressures P_{in} and P_{out} in a Titan 1234 double-shell gas-puff nozzle [2]. Hawk is a unique, current-stiff PRS driver that uses a plasma opening switch (POS) to transfer inductively-stored current into the load, and employs a vacuum voltmeter to directly measure the voltage drop V across the PRS. For a perfect-conductor, the load-voltage measurements permit calculation of the time-dependent load inductance, as well as the associated power and energy in the PRS during the implosion and stagnation phases.

Experiments conducted in 2004 showed that the K-shell yield for nearly-constant load mass was maximum for density profiles corresponding to a range of inner-plenum

pressures 3- to 5-times higher than those in the outer plenum. [1] However, variations in K-shell yield for nominally identical load conditions were not well correlated with peak current or calculated implosion energy. Because of this, a measure of PRS performance was sought that does not depend on implosion history, but is representative of the pinch during radiation. Such a measure is the maximum of implosion power $P_{\text{imp}}(t)$ defined by

$$P_{\text{imp}} = \frac{I^2}{2} \frac{dL_p}{dt} \quad ; \quad L_p = \int V dt / I = 8 \times 10^{-9} \ln \left(\frac{15}{R(t)} \right) \quad (1)$$

where $L_p(H)$ is the inductance of the 4-cm-long load with current return at 15 cm, and $R(\text{cm})$ is the axially-averaged current-channel radius. P_{imp} is large for high compression and/or high implosion velocity, and is low when instabilities, asymmetries, or zippering limit compression. For the data in Ref. [1], and recent data for which the load mass was varied with constant profile shape, P_{imp} , its time integral $E_{\text{imp}}(t)$, and R (from L_p) are combined with K-shell radiation measurements to provide insights into the physics of the PRS stagnation phase. Results for the near-constant-mass $P_{\text{in}} + P_{\text{out}} = 110$ Torr profile study are considered first, followed by those for the constant-profile load-mass study during which $P_{\text{in}} = P_{\text{out}}$ was varied.

II. CONSTANT $P_{\text{in}} + P_{\text{out}}$

The variation in K-shell yield with P_{in} for the profile study [1] shown in Fig. 1 displays shot-to-shot scatter for loads with the same P_{in} . Gas-puff density profiles measured by Laser Induced Fluorescence (LIF) [3] show that equal pressures in the two nozzles contribute nearly-equal masses: $m \approx 0.083(P_{\text{in}} + P_{\text{out}}) \mu\text{g/cm}$ for pressure in Torr. For Hawk, peak current does not vary significantly with profile or implosion time, so that the highest yield with most mass from the inner nozzle supports similar Ar gas-puff results on Double Eagle. [4] Electrical and radiation traces for two of the $P_{\text{in}} = 90$ Torr shots are compared in Fig. 2. Note that peaks in P_{imp} correspond to those in the K-shell power $P_K(t)$. At, or after, the end of the x-ray pulse, P_{imp} crosses zero, implosion energy E_{imp} is maximum, and R is minimum. When P_{imp} is negative, the current channel expands, and the plasma gives energy back to the magnetic field. For shots 3991 (Fig. 2a) and

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14. ABSTRACT Hawk is a current-stiff z-pinch driver that uses a plasma opening switch to transfer inductively-stored current into the load, and employs a vacuum voltmeter to directly measure the voltage drop across the neon gas-puff z-pinch. The load-voltage measurements permit calculation of the time-dependent load inductance, as well as the associated power Pimp and energy Eimp in the pinch during the implosion and stagnation phases. For experiments that determine the dependence of neon K-shell yield on the gas-puff density profile at constant load mass, Pimp is found to be a better measure of pinch quality and yield than peak current or implosion energy. For these data, and other data for which the load mass was varied with constant profile shape, Pimp and Eimp are combined with K-shell radiation measurements to provide insights into the physics of the pinch stagnation phase.					
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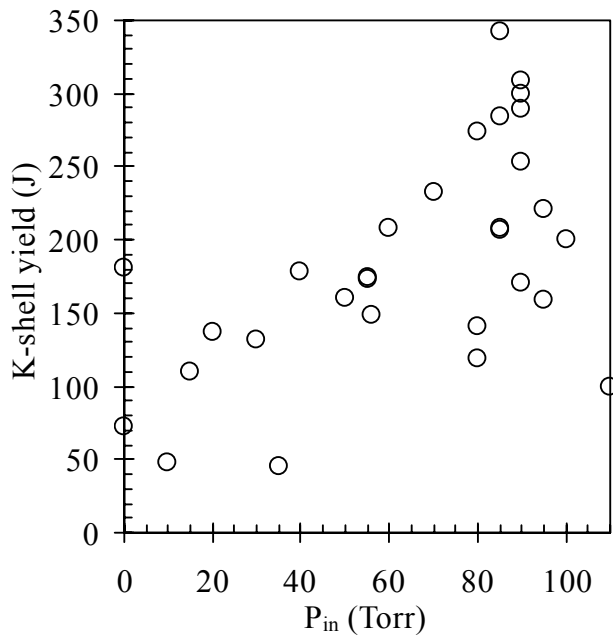


Figure 1. K-shell yield vs. inner-nozzle pressure for $P_{in} + P_{out} = 110$ Torr.

3984 (Fig. 2b), the K-shell yields were 300 J and 171 J, respectively. These shots had similar peak currents and E_{imp} values at the maximum K-shell power, so that P_{imp} is a better measure of PRS performance.

As different axial regions of the pinch stagnate and radiate, P_{imp} remains positive. Implosion energy therefore increases throughout the x-ray pulse in Fig. 2, reaching a maximum $E_{imp(max)}$ nearly double the value at the start of radiation. Because $R(t)$ is an axial average of the current-channel radius, and parts of the pinch are still imploding while the PRS is radiating, R does not reach its minimum stagnation value R_{min} at least until radiation ceases.

The scalings of K-shell yield for the profile-study shots with the maximum of P_{imp} (GW) and E_{imp} (at the time of x-ray maximum) is shown in Fig. 3 along with the $\pm 25\%$ limits of the fit $17P_{imp(max)}^{3/4}$. The figure shows reduced scatter in yield when plotted against $P_{imp(max)}$, demonstrating it to be the better measure of implosion quality. Both the peak and average (yield/x-ray fwhm) K-shell power, not shown in the figure, vary roughly like $0.3P_{imp(max)}$. The average K-shell pulse-width, defined as $E_K/P_K(max)$, varies crudely like $65/P_{imp(max)}^{1/4}$ ns with factor-of-2 shot-to-shot scatter at low P_{imp} , where pinch behavior may be expected to be more erratic.

The pinch lifetime Δt , defined as the interval between $P_K(max)$, soon after the start of radiation, and $E_{imp(max)}$, when the current channel starts to expand, is plotted against $P_{imp(max)}$ in Fig. 4. A similar variation of Δt is obtained when plotted against K-shell yield or $E_{imp(max)}$. Since the K-shell pulse width is never more than about 100 ns, these data indicate that on weak shots, energy is fed into the pinch long after K-shell radiation ceases, perhaps being radiated away as softer radiation. Similar behavior is observed for high-mass loads discussed in III.

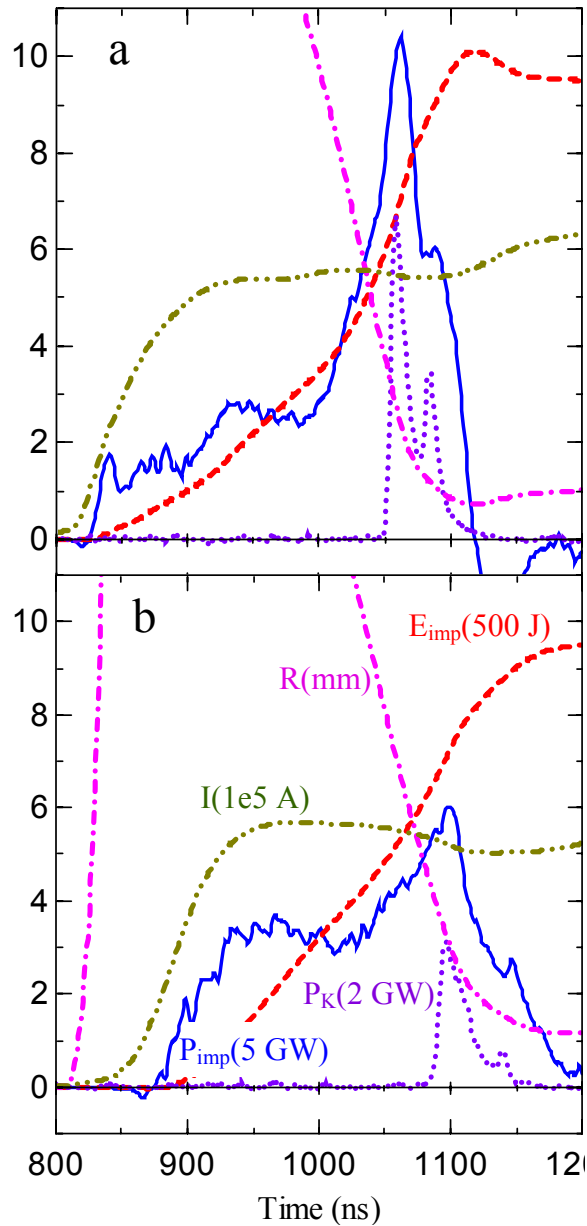


Figure 2. Electrical and radiation traces for two shots with $P_{in} = 90$ and $P_{out} = 20$ Torr.

III. MASS VARIATION WITH $P_{in} = P_{out}$

For the profile study in II, yield variations are attributed to differences in implosion quality as measured by P_{imp} . Here, load mass is varied with a fixed gas profile by varying both nozzle pressures with $P_{in} = P_{out}$. In this case, zero-order variations of K-shell yield with mass limit P_{imp} as a measure of implosion quality to shots with similar mass. However, the analysis can be used to probe differences in stagnation dynamics between low- and high-mass loads, and to compare measured K-shell yields with radiation modeling [5] using measured shot-averaged implosion energy and stagnation radius. Hawk with a

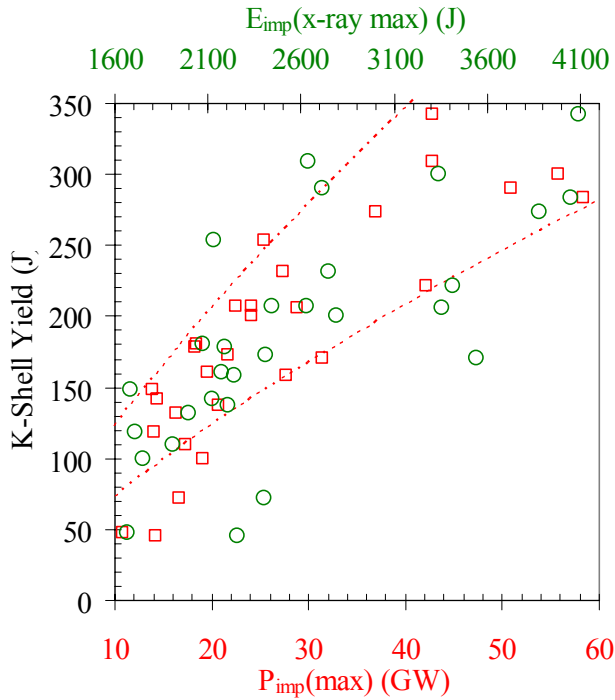


Figure 3. K-shell yield vs. $P_{\text{imp(max)}}$, squares, and $E_{\text{imp(x-ray max)}}$, circles, for $P_{\text{in}} + P_{\text{out}} = 110$ Torr. The lines are the $\pm 25\%$ limits of the fit.

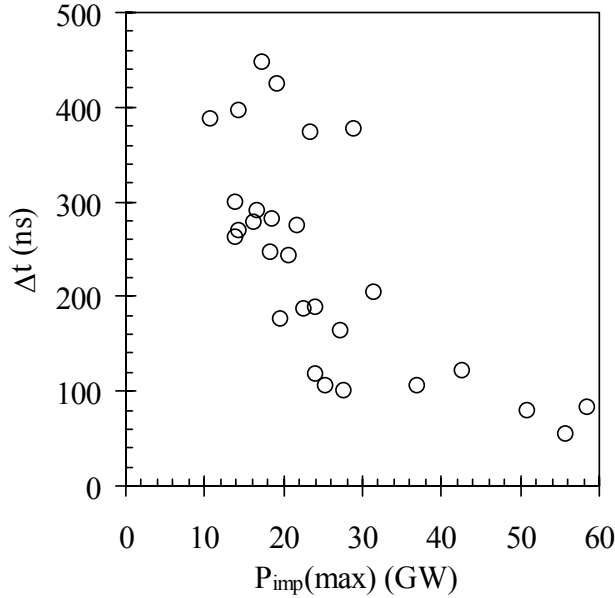


Figure 4. Pinch lifetime vs. $P_{\text{imp(max)}}$ for $P_{\text{in}} + P_{\text{out}} = 110$ Torr.

POS is particularly useful for such experiments because the current is nearly independent of load mass and implosion time and stays nearly constant throughout the stagnation phase, thereby simplifying modeling.

Radii from inductance at the times of $P_{\text{imp(max)}}$ and $E_{\text{imp(max)}}$ are plotted in Fig. 5 as a function of $P_{\text{imp(max)}}$ for the shots of the load-mass study. For the earlier time, R is larger than at the end of stagnation because part of

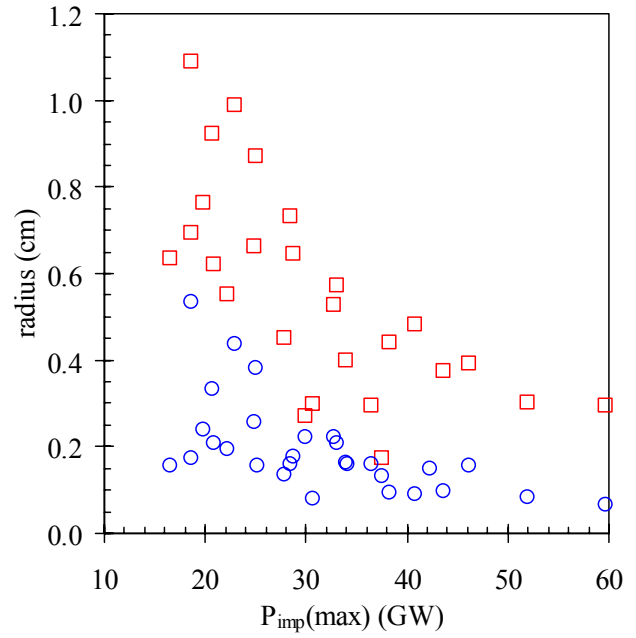


Figure 5. Current-channel radius vs. $P_{\text{imp(max)}}$ for $P_{\text{in}} = P_{\text{out}}$. The squares are at the time of $P_{\text{imp(max)}}$, the circles are the minimum stagnation radius.

the pinch is still imploding and the inductance includes this larger-radius portion of the pinch. For both the profile and load-mass studies, R values at various times during the x-ray pulse scale inversely with $P_{\text{imp(max)}}$, dropping to $R_{\text{min}} = 1$ to 3 mm at the end of stagnation. Values of R_{min} are comparable to those measured on K-shell pinhole images and those of stagnated pinches imaged with shearing interferometry [6].

Results from the load-mass study have been applied to the MQK radiation-scaling model. [5] This model requires as input the imploded mass, the implosion energy, and a single stagnation radius R_s at which the pinch radiates in the K-shell. Given R_s , E_{imp} is determined from snowplow calculations using the LIF-measured density profile [3]. The implosion energy is used in an energy balance equation that determines plasma temperature for the K-shell yield calculation. The stagnation radius is taken to be the average of all values at the time of $P_{\text{imp(max)}}$ shown in Fig. 5: $R_s = 0.5$ cm. The snowplow current rises linearly in 85 ns to a flat-top maximum with a weak pressure dependence that accounts for current-risetime and L-dot-loading effects: $I_{\text{max}} = 0.52$ MA for $P_{\text{in}} = 20$ Torr, $I_{\text{max}} = 0.585$ MA for $P_{\text{in}} \geq 50$ Torr.

Results of the radiation-model/experiment comparison are shown in Fig. 6. The dashed curve shows the MQK model K-shell yield vs. P_{in} , which assumes that all neon ions are stripped into the K-shell. The modified MQK result (solid curve) reduces the yield by the fraction of ions (based on coronal equilibrium) that have burned through to the fully-ionized state. Agreement between the data and the model is gratifying. The two highest-yield experimental points correspond to shots with $R_s = 0.3$ cm,

so that higher yields would be predicted for these higher-quality implosions.

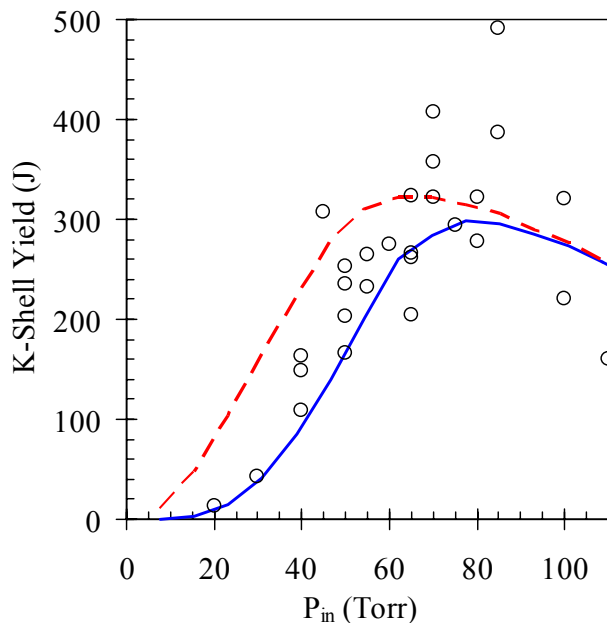


Figure 6. K-shell yield vs. P_{in} for $P_{in} = P_{out}$. The dashed line is the prediction of the MQK model, the solid line is MQK reduced by the burn-through fraction to the fully-ionized state.

IV. CONCLUSIONS

Direct measurements of the voltage across the Hawk neon PRS has provided insights into the physics of the stagnation phase. During stagnation, the implosion power follows the K-shell power and provides a good measure of implosion quality with constant load mass and different density profiles. The implosion energy increases by about a factor-of-two during stagnation. This result may help to explain discrepancies between the total radiated energy and the computed implosion energy in experiments without reliable voltage measurements during stagnation. Stagnation-phase lifetimes are observed to be several-hundred ns on shots with poor implosion quality or high mass, suggesting that the pinch continues to radiate in softer radiation once K-shell emission has ceased. Preliminary bare-XRD measurements on Hawk, as well as bare-XRD and bolometry measurements in Decade Quad argon gas-puff experiments [7], support this conjecture. The radius of the current channel on Hawk at the end of stagnation is comparable to those of K-shell pinhole and shearing-interferometer images. K-shell yields from the MQK radiation-scaling model agree with the measured values over a wide load-mass range when the shot-averaged stagnation radius and current history are employed.

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